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6 LONG PERIOD SEISMIC WAVES,

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OBSERVATORIO SAN CALIXTO

La Paz - Bolivia

Final Report

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A

ABSTRACT

A High-Gain Long-Period seismic station (ZLP) was installed in a tunnel 90m long in the Zongo Valley (16°16'10.3"S, 68°07'05.3"W, 4397m asl), where daily barographic changes do not exceed 3 mbars, to obtain high quality data both for Federal agencies research and for Observatorio San Calixto research. A microbarograph and standard meteorological instruments were added for convenient correlations. Also short-period seismographs, with a gain of one million for one second of period, were installed.

Operation has been maintained and magnificent records were and are still being produced. Vertical seismic noise of 20 through 100 sec of period was proved to be produced mostly by atmospheric disturbances, with a numerical relation of 2.5 to 5 millimicrns/microbar; horizontal waves are associated with wind.
The coefficients of the formula for calculation of seismic events local magnitude were found to be as it follows: $M_L = \log(A/T) + 1.51\log D + 2.0$ for distances around 5 degrees.
The study of internal structure of the earth has shown an important friction in the earthquakes occurring at the lithosphere bending. Models were developed and are presented for the seismic velocities as a function of depth beneath La Paz region, differing a little from one azimuth to another.

Several techniques were tested to discriminate explosions from natural earthquakes; both Love and Rayleigh waves are quite better developed for earthquakes than for explosions: the ratio $A_Q:T_Q$ / $A_R:T_R$ is much greater for earthquakes than for explosions in most of the spectrum.

Subducted Nazca plate appears in different strips undulated or broken apart, according to the angle offered by South American plate. Correlations were done between gravity, strain release and metalbgenesis as related to the subducted Nazca plate: a close relation was found (but the study has to be continued).

As a contribution to seismicity studies, the main results of a particular earthquake are presented, together with a preliminary seismic risk map estimated according to epicenter locations and macroseismic data.
An attempt of Rodríguez and Vega to quantify seismic risk, by defining relative weight of maximum MM intensity at a given distance, population density, area geology and attenuation of intensity with distance, is presented together with a map applying theory to Bolivia.

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LONG PERIOD SEISMIC WAVES

INTRODUCTION

The operation of Peñas Seismic Station (PNS) by the Observatorio San Calixto under AFOSR Grants 792-65, 68-1614 and 72-2177 together with similar experiments has shown the possibility of lowering seismic noise about two orders of magnitude and consequently of recording long period seismic waves at extremely - high magnification. This way, a large number of earthquakes, also of low magnitude, either natural or manmade, may provide information both about the path of these waves and about their source.

On the other hand the study of seismic waves longer than 20 seconds has proved to be very useful to know better and better - the interior of the earth.

Until now, no other similar seismic station exists in this - part of the world. The one operated under this Grant was installed in a tunnel excavated especially for this purpose by - the U.S. National Oceanic and Atmospheric Administration, - through a contract with the Observatorio San Calixto, in the - Valley of Zongo, at 32 miles from La Paz downtown (16°16'10.35" S, 68°07'05.3"W, 4397 m. asl.). Zongo station is known by the abbreviation ZLP.

The tunnel opens in a granite wall at the foot of Huayna Potosí mountain (its peak is at 6080 m. asl. at an horizontal distance of about 3.5 Km), so the seismometers are some 300 m. below - surface.

Atmospheric pressure changes (what influence notably seismic -

noise) at this altitude are not significant, about 3 millibars the daily change, being the mean pressure 602 mbars.

In these conditions the experiment has had two general objectives: adquisition of high quality data, to be offered to the United States investigators, especifically those of research Federal agencies; research at the Observatorio San Calixto. Both goals have been achieved in a high level, as it will appear along the present report.

The Observatorio has installed meteorological instruments, a part of them financed by this Grant, to correlate seismic noise with meteorological variables.

Research plan has been rather ambitious for the personnel and financial possibilities, but most of the problems initially considered have been tackled with some success.

First of all, noise had to be studied, mostly in order to look for any possible improvement in lowering it and consequently for the records improvement; but also it was convenient to look for any useful applications of noise measurements.

The Central Andes area is known to have a rather complex structure so that seismic waves through it are highly attenuated; that means a large influence in the recorded amplitude and consequently on the magnitude determination. To quantify such an influence has been another goal of Grant research; it is important for any use of magnitudes and especifically for the purpose of discriminating explosions from natural events.

The area structure itself is interesting not only for regional purpo es, but because it influences waves recording potentially distorting any study using those records. So, it was intended to investigate seismic waves velocity as a function of depth, attenuation, surface waves dispersion, in order to get a better insight to the thickness of crust and composition of both crust and mantle. The interest was mostly concentrated in the behavior of the Nazca Plate subducted beneath South America -

controlling Andean seismicity, gravity, metallogenesis, etc.

Bolivian seismicity, of a very uneven degree along the country geography, had to be studied for humanitarian purposes, for - comparison with other countries seismicity in order to obtain a better insight into seismic phenomena and for a better in-- terpretation of seismic records; so, it was another goal of - Grant research.

INSTRUMENTATION

Long period GEOTECH seismometers especially designed to work - with very high magnification (as at Ogdensburg, New Jersey, - OGD, and other similar stations) were installed within the tunnel mentioned above, at 70 m. from the entrance. (Fig. 1).

The tunnel is 20 m. longer, but this part had to be closed, because a rather large water flow through granite fractures was encountered inside there, creating the problem of extracting - the water without opening a way to atmospheric pressure oscillations in the chambers to be crossed by the pipe. A part of this water was recovered at the top of the tunnel to be used - in the neigbor photographic laboratory of the station and the rest was taken along the tunnel by a pipe maintained under some hydrostatic pressure, that sufficient to damp atmospheric - pressure oscillations.

The seismometers were installed in September-October of 1972 by the personnel of Albuquerque Seismological Laboratory (Messrs. Hut, Hampton and Castellani), assisted by the Observatorio personnel (Messrs. Flores, Marco S.J., Cosulich). Each seismometer was closed within a steel dome, covering a steel tank bolted to the bedrock and cemented to the floor by an especial procedure and closed with a large number of clamps. Three ship - bulkhead doors (type A in Fig. 2) and other four steel doors - worked at La Paz (type B in Fig. 2) separate different chambers insulating strongly the inner ones.

Signals obtained from transducers were amplified by photo tube amplifiers until July 1975. It was necessary to isolate PTA - amplifiers from environmental humidity by means of a steel water-proof dome; this proved to be a very good remedy. Since - 1975 signals are amplified by solid state electronic amplifiers.

Records are obtained on broad band digital magnetic tape -- through ASTRODATA Data Logger and on photographic paper with - two levels of magnification, "high" meaning more than 200,000

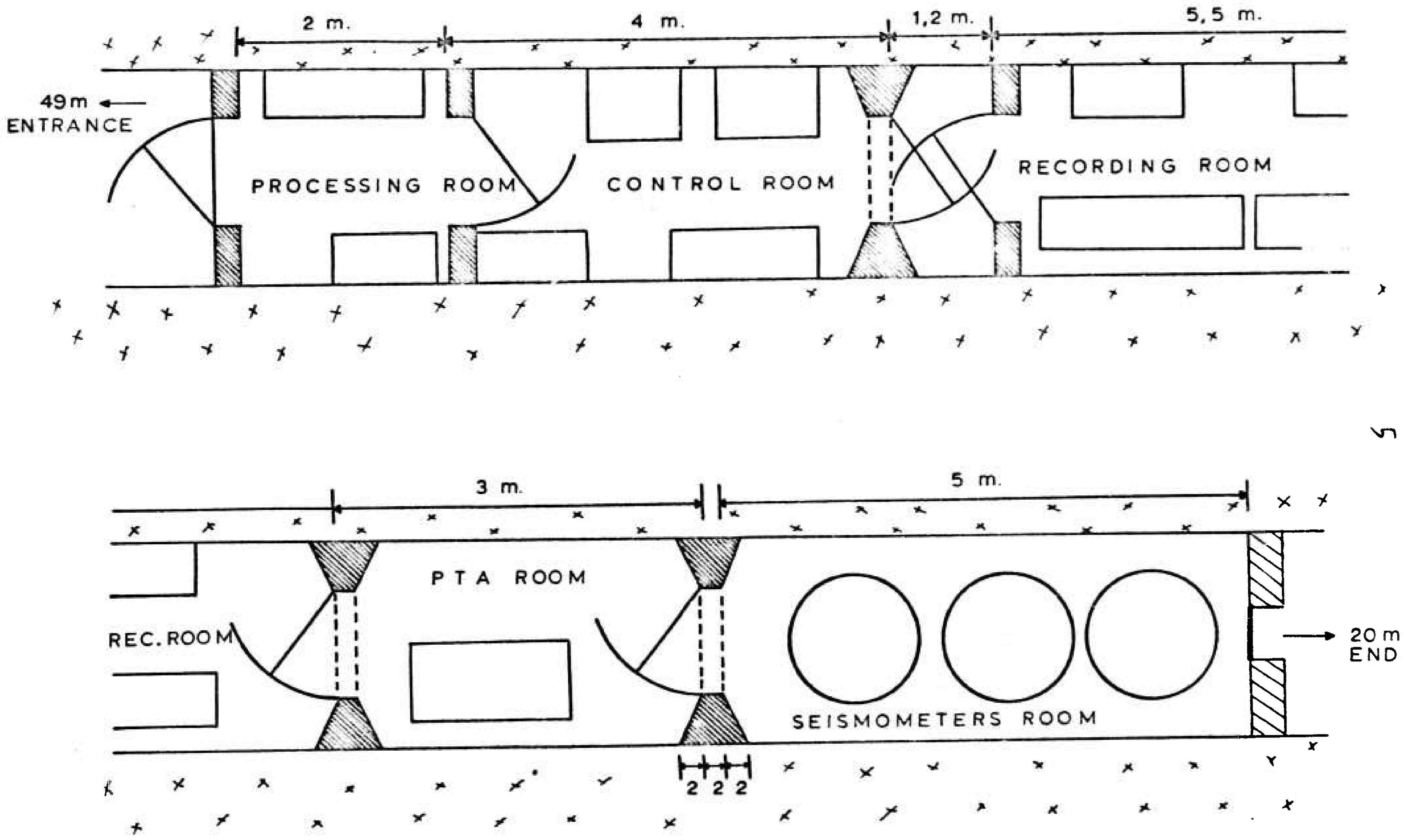
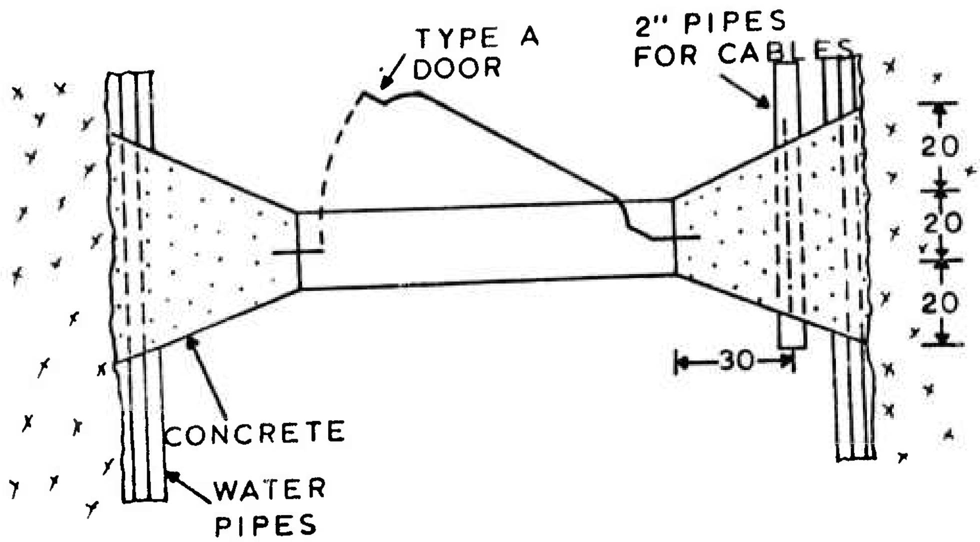


Fig. 1.- Installation inside the tunnel of ZLP.



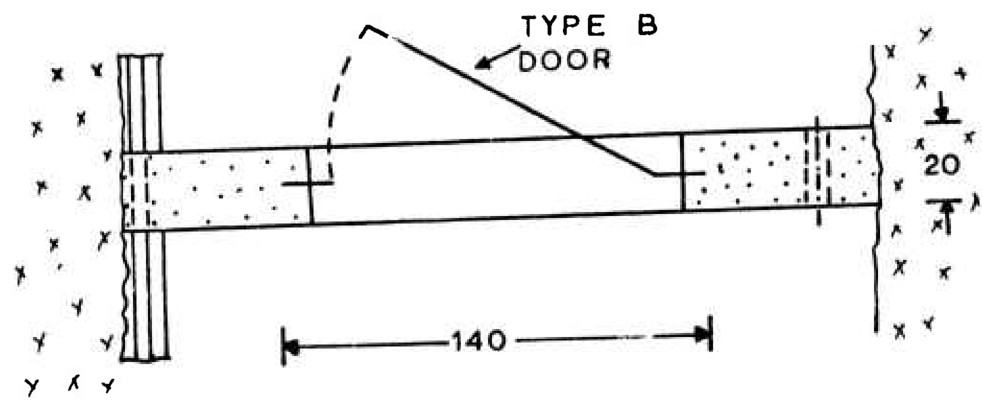


Fig. 2.- Bulkhead ship door (type A) and flat door (type B), as installed in ZLP tunnel. The shape of concrete mounting distinguish both types in fig. 1.

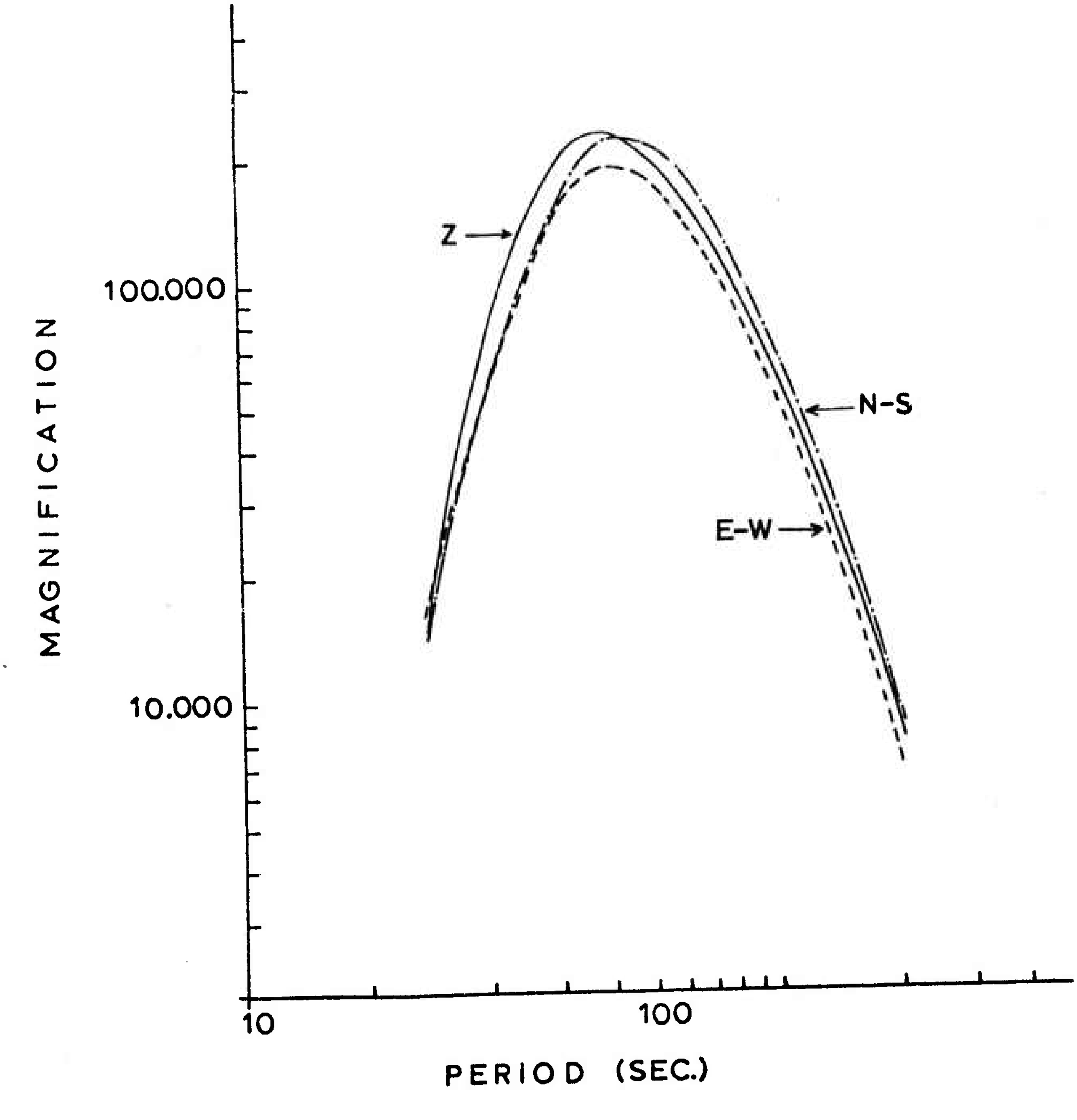


Fig. 3.- Magnification curves of ZLP long-period instruments.

for the vertical component and about 150.000 for both horizontals North-Sourth and East-West (Fig. 3), "low" meaning about 4.000 in all three components. It has to be noticed that - ground noise of 40 seconds of period is only 0.02 to 0.05 mi-- crons. So, most of surface waves produced by surface earthquakes of magnitude 3.1 originated anywhere in the world, excluding nodal planes, are recorded there. Displacement components have been recorded on paper rolls by means of Esterline-Angus recorders since 1974. Time signals are obtained from a quartz digital clock.

A microbarograph for the period range 10 through 1000 seconds was installed to measure air pressure oscillations (related to seismic long period noise, as said above). Close to the tunnel entrance a meteorological station was installed and has - been maintained with no interruption.

Since July 1973, a short period vertical seismograph has been operating in the same tunnel; in May 1975 three short period - components were installed. Allthree components are recorded - on 35 mm film at an approximate gain of 1000K for 1.0 sec of - period.

Electrical power is obtained from a hydroelectric plant supplying power to La Paz city, sited at about 500 m. Electrical - current is regulated at the entrance of the tunnel with the - aid of a large battery set.

The main instruments occupy 21 m. of tunnel; the floor of this part was poored with cement; walls and roof were also covered with cement by the gunite method up to a thickness of about - 0.5 cm.

A small house had to be built near the tunnel to house the technician caring routine operation.

Maintenance has been performed by electrical Engineers José - Flores, Raúl Cosulich, etc., driving there any time it has - been necessary, but in any case not less than weekly.

INVESTIGATION

Noise

First of all, seismic long-period noise was analyzed, trying to detect its sources and any possibility of lowering it. Noise of 30 to 40 seconds periods appeared the most prominent peak - in the spectrum, followed by another peak at 80 to 90 seconds.

It was realized that atmospheric pressure oscillations (infrasound) are highly damped inside the tunnel by the steel doors and seismometer tanks; a microbarograph in the seismometers - room measured amplitudes of infrasound of the order of one microbar for waves of 600 sec period and almost a total absence of shorter period waves. Nevertheless a cross-correlation between seismic (seismometers room) and infrasonic (outside the - tunnel) records has shown that vertical seismic noise in the - range of 20 to 100 sec is produced mostly by atmospheric disturbances, without doubt by the coupling of atmospheric and solid earth waves at the free surface; horizontal waves are asociated with wind and lateral motion of the Huayna Potosí mountain under which Zongo station is located.

Our results show a numerical relation of 2.5 to 5 millimicrons/ microbar, depending on the mode of the acoustic wave propagation. It may be remarked that it is 1/4 of the value theoretically found by Sorrells for the sandstone of Great Saline (granite in ZLP).

Magnitude calculation

To get the formulae the best suited to calculate magnitudes after ZLP records, the amplitudes of P, S and L waves of 305 - events of the year 1973, ranging in magnitude from m_b=3.7 to m_b = 6.4 and epicentral distances from 2^o (22 Km) to 165^o - (18300 Km) were measured.

It was found by the least square method that the best suitable magnitude calculation for near events ($D \cong 5^o$) is given by:

$$M_L = \log\left(\frac{A}{T}\right) + 1.5 \log D + 2.0$$

where A is the L_R maximum amplitude in millimicrons, T its period in seconds and D the epicentral distance in degrees.

Fault Friction

Friction in different parts of the Nazca plate was studied. Friction appears to be especially important in the source mechanism for earthquakes located at the lithosphere bending; on the contrary the importance is minor in the deepest part of subducted plate. The result is interpreted in relation to thermal regime of the underthrusting slab with depth.

Crustal and Upper Mantle Structure

A study of P and S waves residuals, a continuation of those achieved under Grant AFO R 72-2177, has confirmed that the crust is very thick (about 65 Km) beneath the Central Andes, overlying a thick lithosphere to a depth of 300 Km; this is continued by a low velocity layer again thick coincident with the "earthquakeless zone". Local anomaly residuals were found between PNS and LPB stations, being atttributed to a very local superficial low velocity layer, corresponding to a gravity anomaly and possibly to the "magma pockets" found by Sacks (1971).

Local low velocity paths agree well with low Q values, which in turn depend on depth. The combination of both earth structure and Q variations with depth is the best way to account for the observed amplitude spectral ratio of waves recorded at Arequipa and La Paz at each side of the Central Andes Cordillera.

PcP and ScS phases are of very small significance; that yields large structural irregularities underneath the Central Andes.

It was demonstrated theoretically that vertical componet of noise may be used to describe the structure of the uppermost superficial layers, until several meters of depth, through a correlation with atmospheric infrasonic waves. A long-period vertical seismograph should operate for a short time together with a microbarograph: the cross-correlation of both records should show a strong dependence on the structure of the upper-

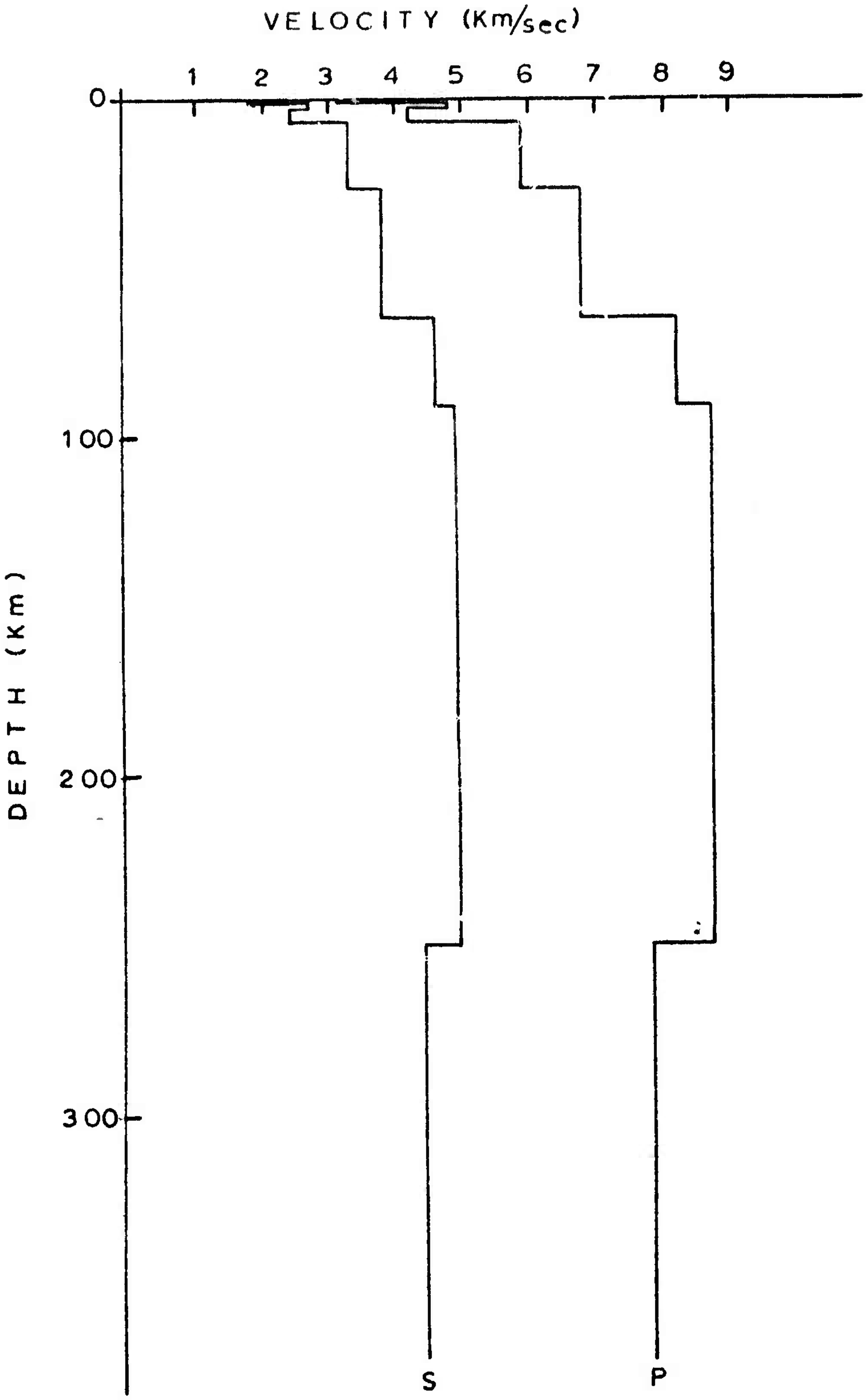


Fig. 4.- Model of underground structure beneath Central Andes, obtained through inversion of seismic residuals for Sandwich Is. region earthquakes.

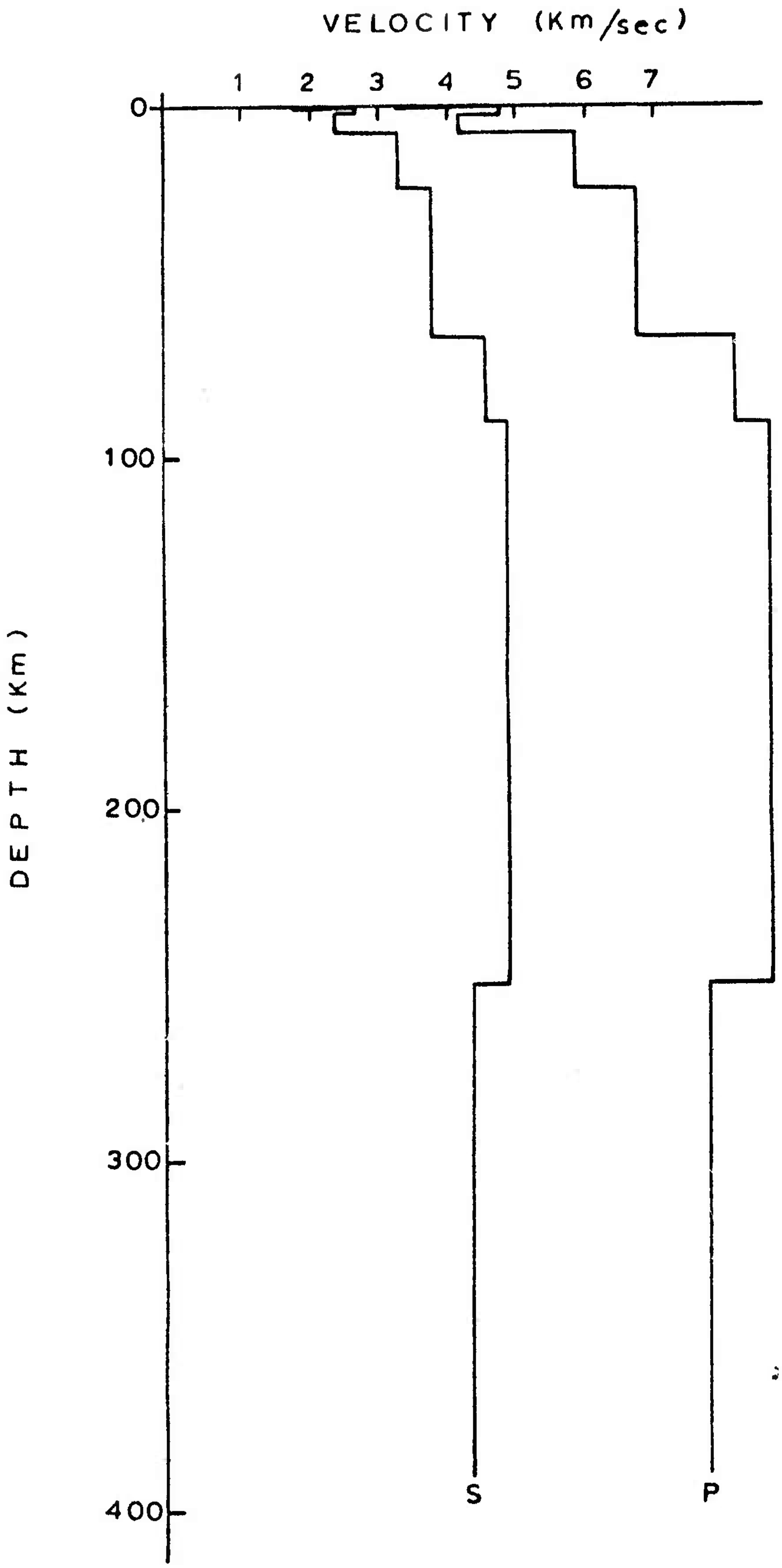


Fig. 5.- Same as fig. 3 for Easter I. region earthquakes. Small differences may be noticed, since structure changes according to the azimuth.

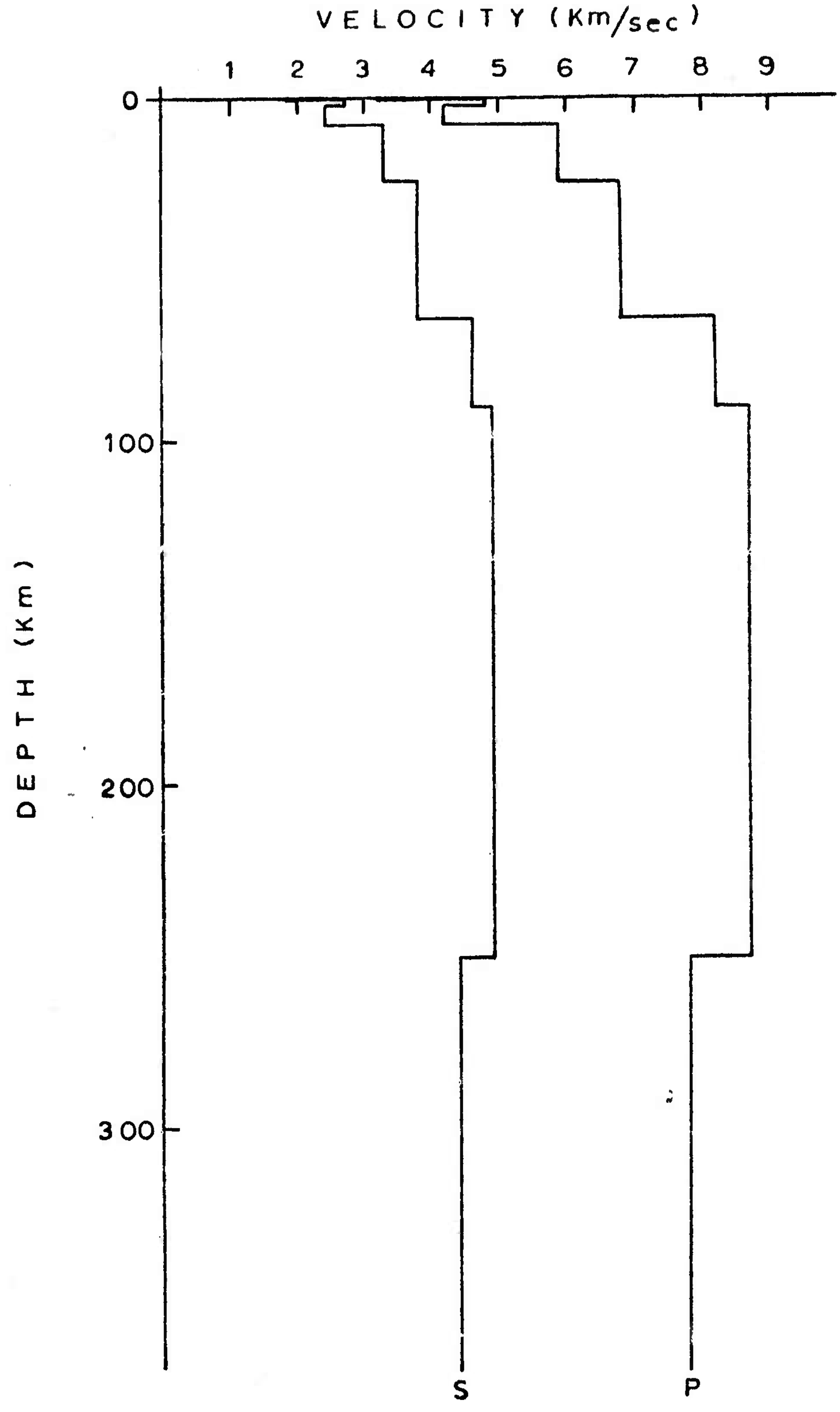


Fig. 6.- Same as figs. 4 and 5 for Chiapas, Mexico, earthquakes.

most layers.

Dispersion of surface waves was also used to calculate crustal thickness. For the events located in Nevada and California - part of the path is oceanic; so, a correction was necessary to normalize those events as if the path would be completely continental; this way the mean crustal thickness for Western United States with the Andes along Colombia, Ecuador, Peru, Bolivia was found to be 57.6 Km.

Discrimination Techniques

After trying several techniques to discriminate artificial events from natural earthquakes, two of them using long-period waves have proved to be efficient and easy to be handled, at least for Nevada and Russia events, for which these techniques were applied.

The amplitude over period ratio of Love to Rayleigh waves:

$$\frac{A_Q/T_Q}{A_R/T_R}$$

is much greater for earthquakes than for explosions. Certainly it is a function of magnitude and distance, but so slightly that it may be considered constant for a given region.

Both types of surface waves are quite better developed for natural earthquakes than for explosions.

Surface waves dispersion definitely does not offer any criterion for such kind of discrimination.

Nazca Plate Geometry

An analysis of foci locations obtained by the U.S. Coast and Geodetic Survey, the National Oceanic and Atmospheric Administration and the U.S. Geological Survey, by projecting the foci

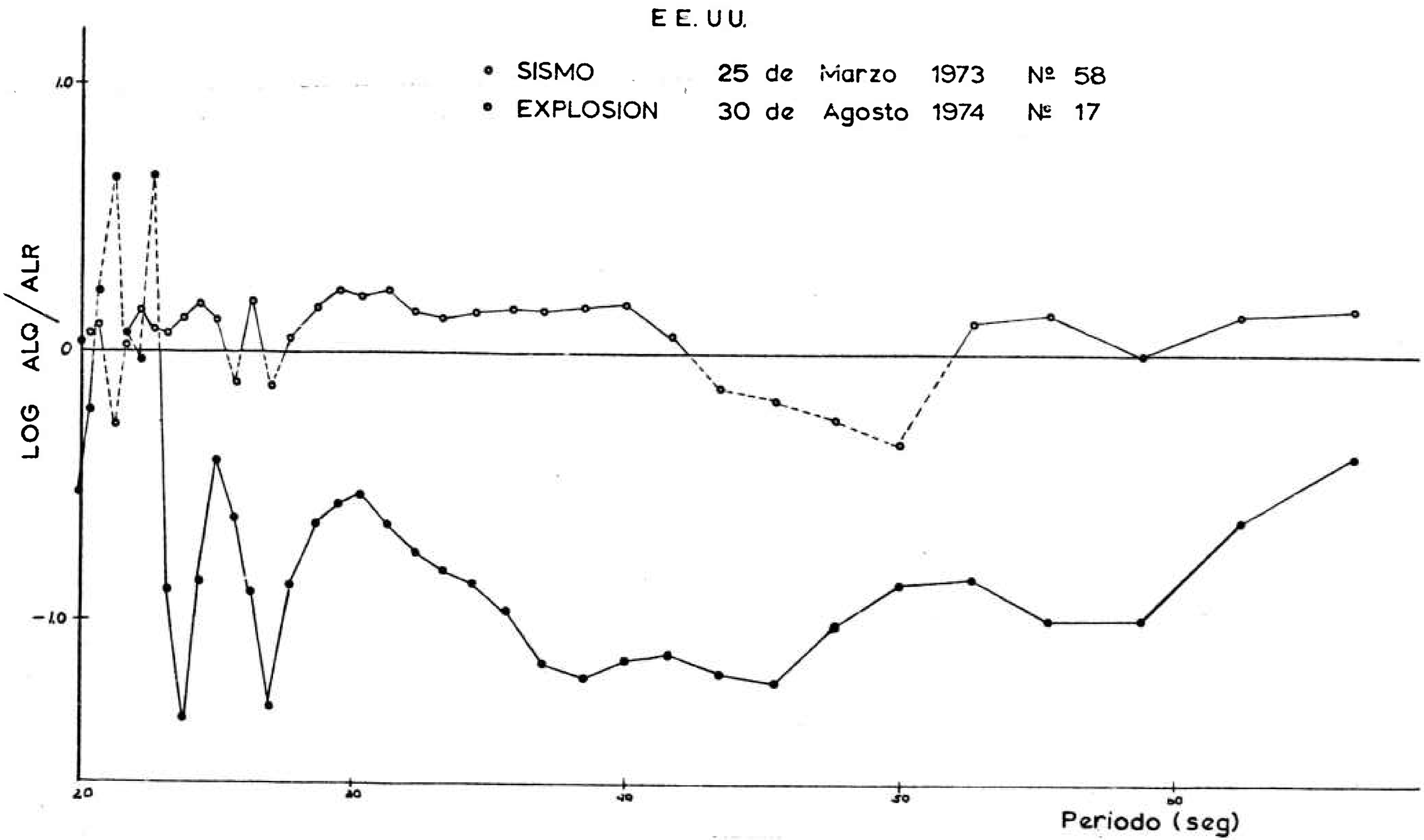


Fig. 7.- Logarithm of the ratio between the maximum amplitude of Love and Rayleigh waves for an earthquake of m_b 5.5 occurred at 25.9°N 109.9°W (open dots) compared to that of an explosion of m_b 5.8 at 37.1°N 116.1°W (solid dots). For periods longer than 25 sec the L_Q amplitude is less than that of L_R. (From Vargas' thesis, 1976)

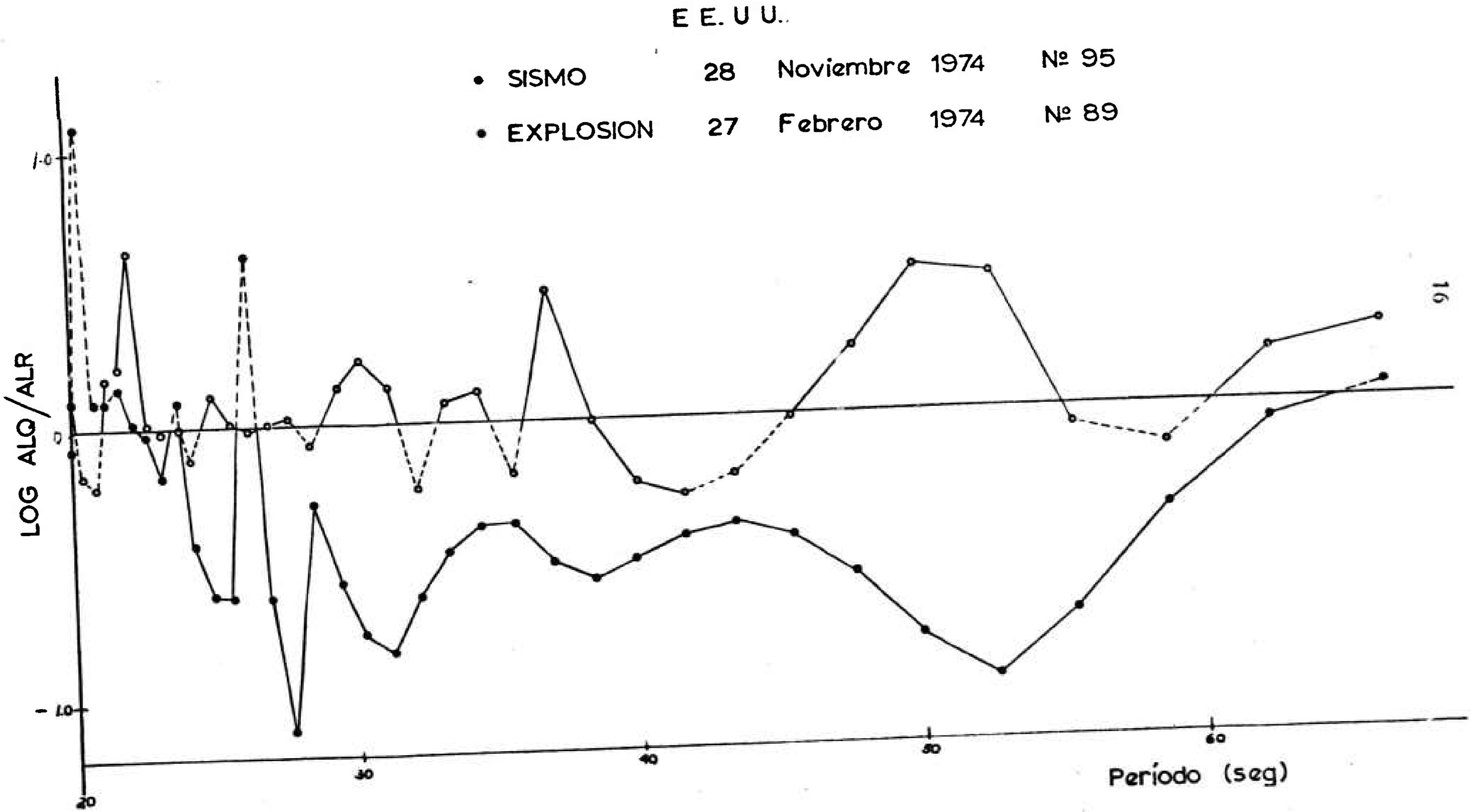


Fig. 8.- Same as fig. 7 for an earthquake of m_b 5.0 at 36.9°N 121.5°W and an explosion of m_b 5.8 at 37.1°N 116.1°W.

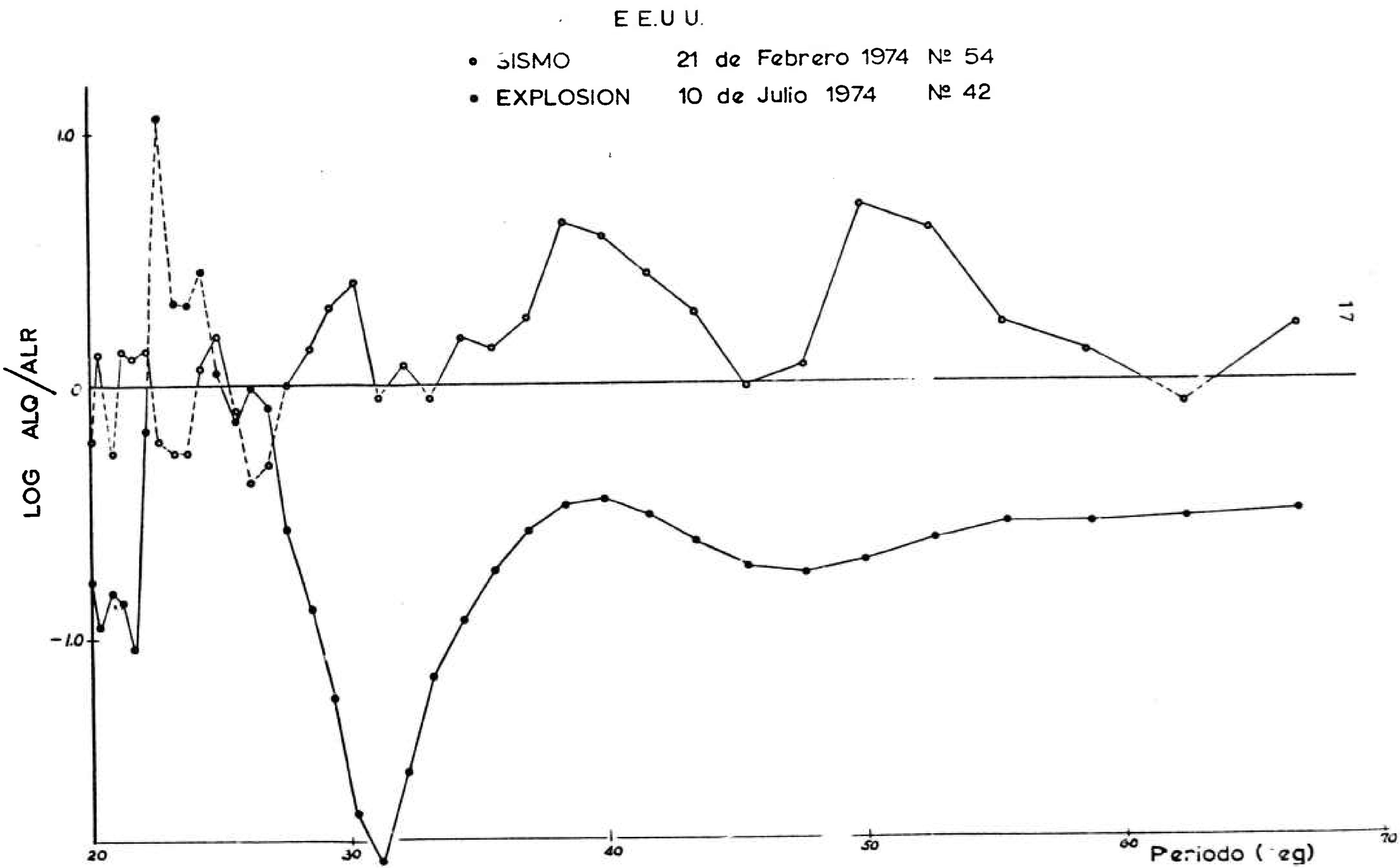


Fig.9.- Same as fig.7 for an earthquake of m_b 5.7 at 34.1°N 119.0°W and an explosion of m_b 5.7 at 37.1°N 116.0°W.

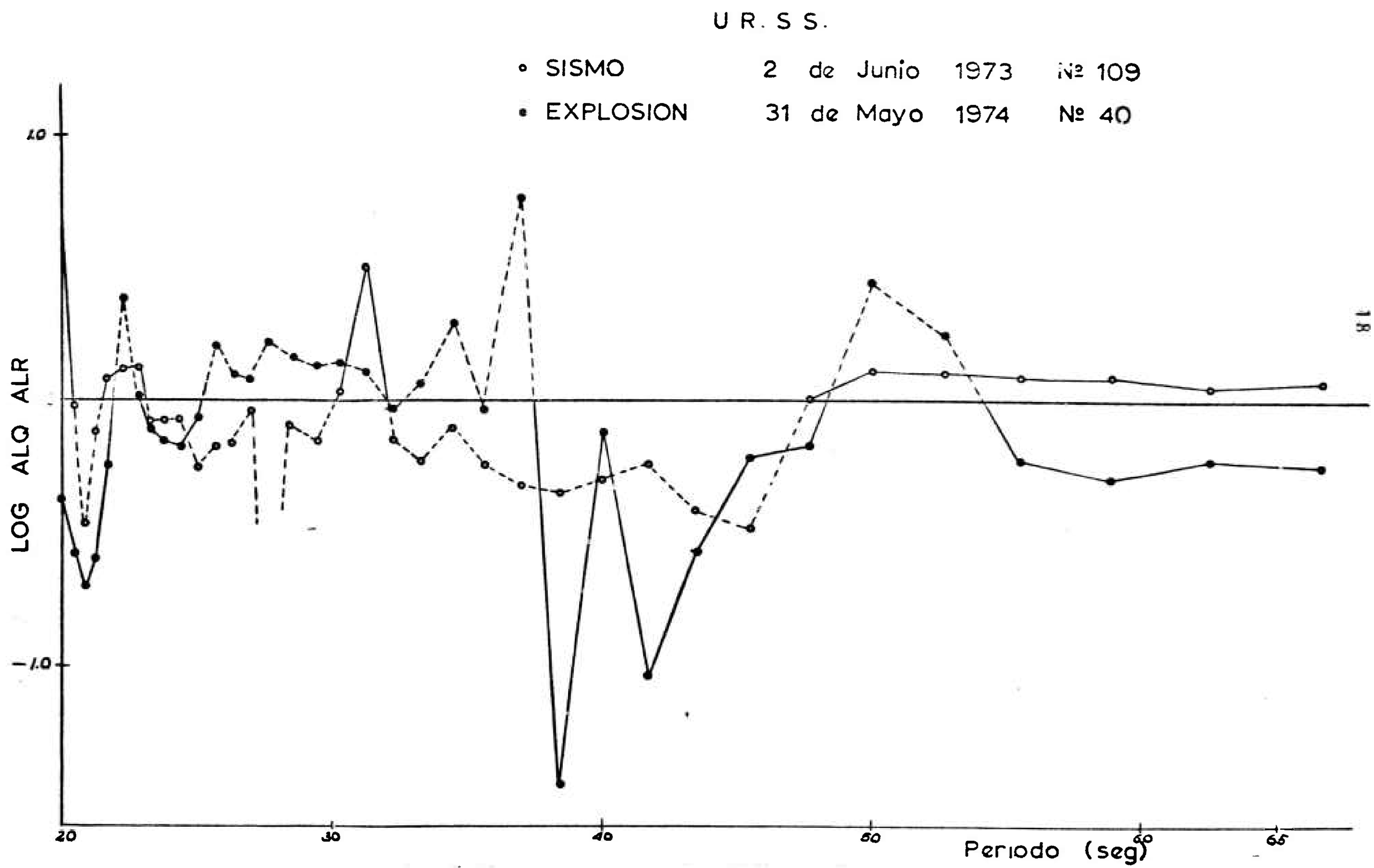


Fig. 10.- Similar to fig. 7 for an earthquake of m_b 5.8 at 44.1°N 83.6°E and an explosion of m_b 5.9 at 50.0°N 78.8°E. For this area (distance between 130° and 145°) L_Q amplitude is surely less than that of L_R only for periods longer than 55 sec.

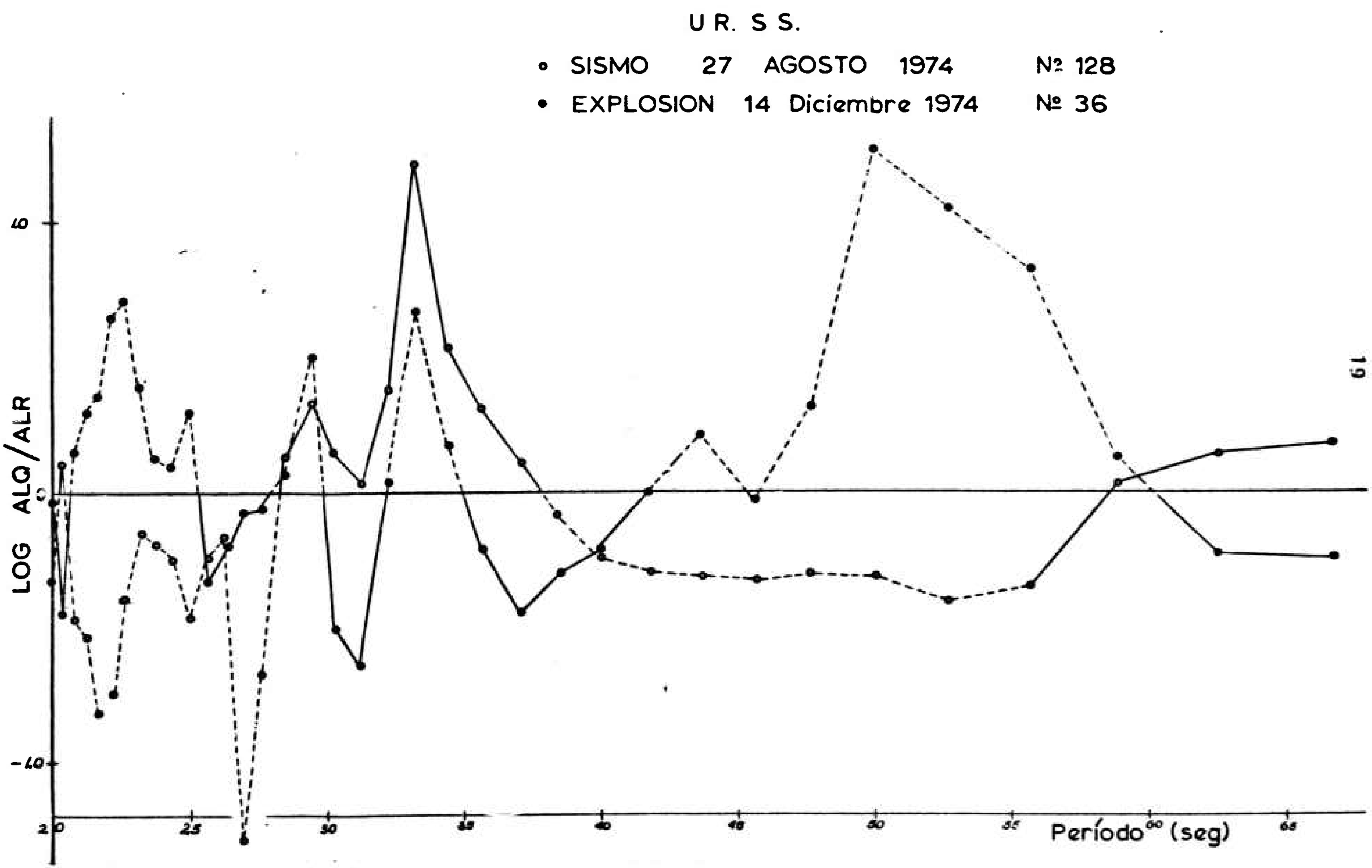


Fig. 11.- Same as fig.10 for an earthquake of m_b 5.8 at 39.7°N 73.8°E and an explosion of m_b 6.0 at 49.8°N 78.1°E.

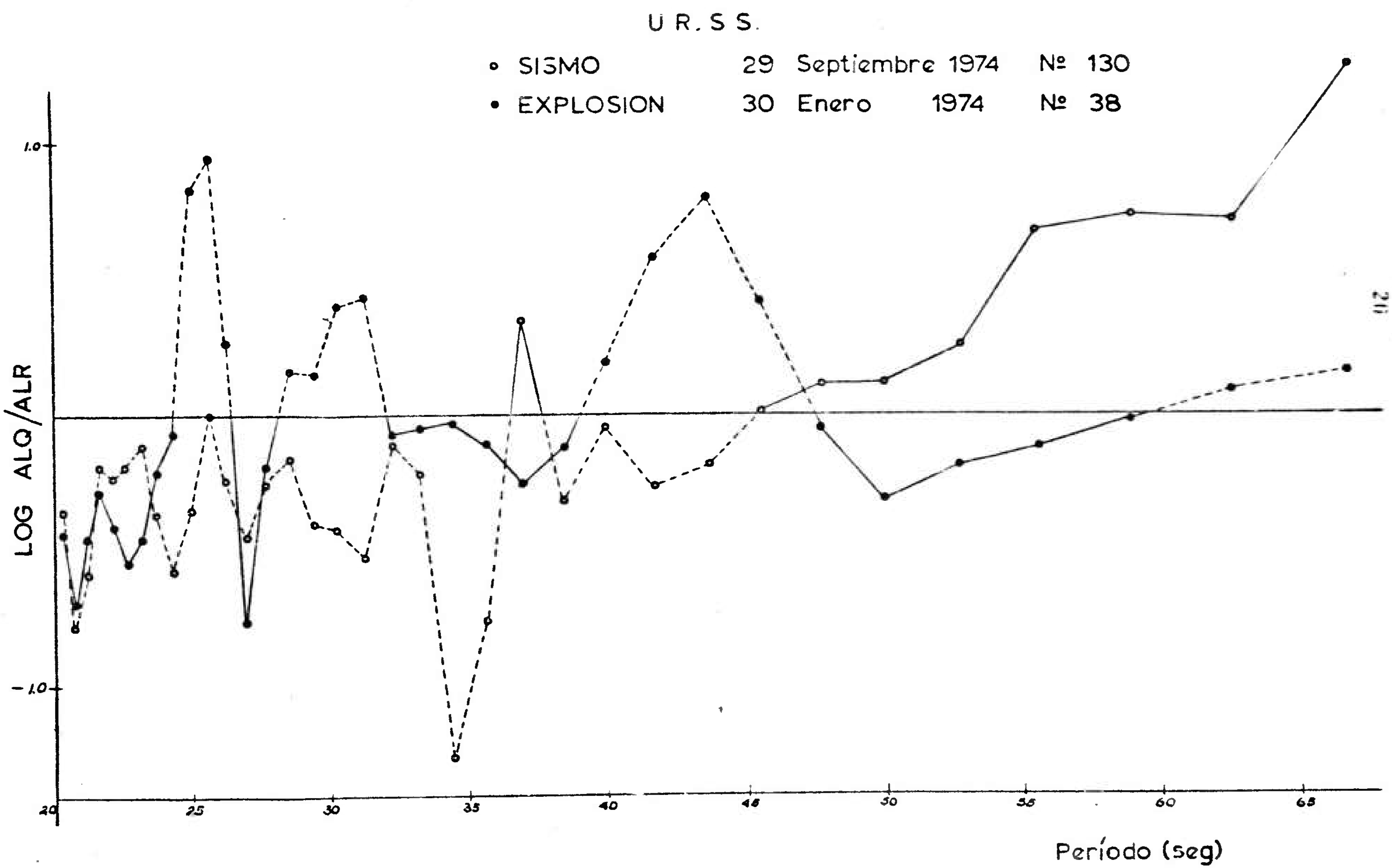


Fig. 12.- Same as fig. 10 for an earthquake of m_b 5.4 at 40.4°N 78.0°E and an explosion of m_b 5.4 at 49.8°N 78.1°E; but this case is an exception so that L_Q becomes a little larger than L_R after 60 sec.

in different strips in different ways, has shown the geometry of the Nazca plate. Actually the work done under this Grant - became a confirmation of the work done under the Grant AFOSR-72-2177 describing the geometry of the subducted Nazca plate.

This geometry is rather complex: the plate is undulated like a curtain, where it strikes the American plate with an angle - of more than 180^{0}; it is broken apart where the American plate offers an angle of much less than 180^{0}.

Practically no seismic activity appears between 300 and 450 Km of depth. By this method one should say that Nazca plate is - not existent at that depth, but probably the real explanation is that the plate with the pressure and temperature conditions of this depth does not sustain any seismic activiy; that means: the plate should be soft and partially molten.

Seimicity

With the assistance of this Grant several contributions were - done to the study of Bolivian seismicity.

On February 22, 1976, the Central Bolivia was shaken by an earth quake of magnitude 5.6 (followed by an aftershock sequence) causing alarm and some damage in villages closer to the epicenter. The Grant AFOSR-72-2397 together with the help of other institutions, assisted for a short survey mission. According to the macroseismic study and time of recording in seismic stations, the focus was about 125 Km deep at 18.43^{0}S, 65.16^{0}W, close to the Quiroga village, not far from Aiquile town. The origin - was a dip-slip fault striking N42.5W dipping 60^{0}W. Macroseismic data, as well as instrumental and historical data were assembled and published, as recensed below. In the formula:

$$\text{Log } N = a - bM_L$$

a and b, constants characteristic of the region, were found to have the following values:

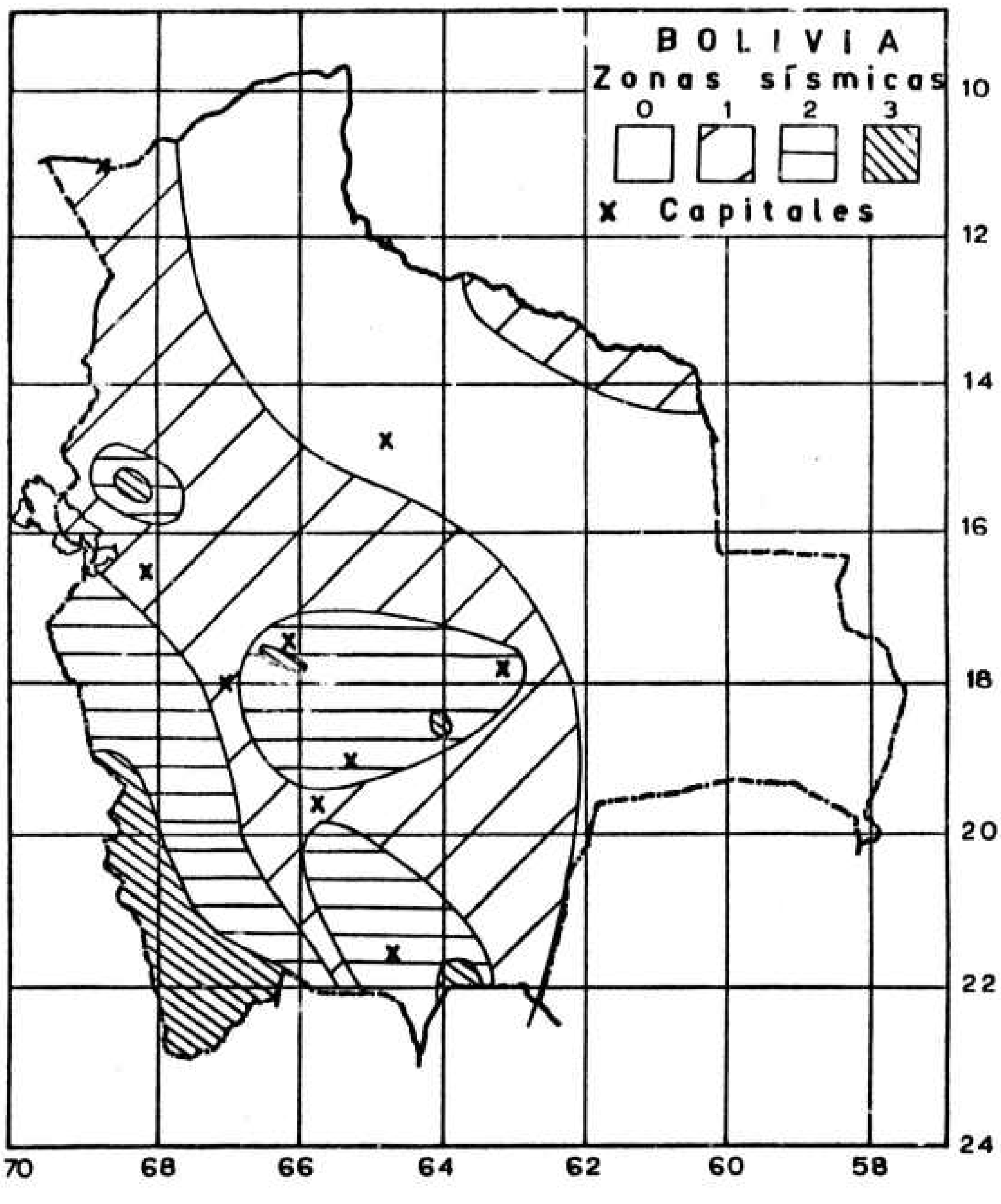


Fig. 13.- Map of Bolivia estimated risk, scale 0 through 3, according to epicenter locations and macroseismic data.

$$\text{Log } N = 2.6084 - 1.1319\ M_L$$

what means a high rate of aftershocks increasing the area danger.

A very preliminary map of seismic risk in Bolivia has been prepared, according both to macroseismic data accumulated in Observatorio San Calixto and to locations of earthquakes obtained by the U.S. Coast and Geodetic Survey (NOAA and U.S. Geological Survey). (Fig, 13).

Attemps are being done to quantify better seismic risk; see below the study of Rodriguez and Vega.

Gravity, Topography, Strain Release and Metallogenesis as Related to the Subducted Nazca Plate.

From previous studies (Rodriguez et al 1975) the close relation between the subducted Nazca Plate, Topography, Gravity and metallogenesis of ore deposits in Bolivia was demonstrated. The following is a brief summary of the results of a continuation of the same type of investigation under new data gathered.

Preliminary maps of areal distribution of mines were prepared for the whole territory, separately, according to mineral type, showing interesting features very useful for regional prospection programs.

The frequency analysis of each to these maps reveals also intriguing correlations with the subducted plate at the time of the emplacement of such deposits. Geochronological analysis of the intrusives also correlate very closely with these phenomena.

Seismic, gravity and strain release profiles along the maximum dip of the Nazca Plate at different latitudes were used to study the geodynamical behaviour of the plate and to obtain essentially possible sources of magma differentiation at the time -

when the Occidental and Oriental cordilleras were formed and - the minerals emplaced. It is very consistent the fact that at almost any time Geochemical and Physical conditions prevaled - at a depth of 300 Kms. point out the region as the principal - magma differentiation zone very well correlated with the seismicity, gravity data and upper mantle structure.

Secondary magma differentiation regions were also found at different levels in different latitudes and very closely related with the geometry of the Nazca Plate.

The complicated picture of the metallogenetical zones of ore deposits in Bolivia seems to reflect the complication in the geometry well correlated with the temperature regime of the plate.

This research is being continued after the end of the Grant, - though financial support is not granted.

SEISMIC RISK OF BOLIVIA. René Rodríguez and Angel Vega.

To quantify the Seismic Risk of Bolivia a parameter called Index of Seismic Risk has been defined based upon the local seismicity given by the maximum modified Mercalli Intensity, population factor, geological factor and attenuation of Intensity with distance. This parameter is matematically formulated as:

$$ISR = K\ In\ D\ G$$

where:

In = maximum intensity (MM) at a given distance

D = population density $0 < D < 1$

G = geology factor $0 < G < 1$

$K = \dfrac{Rmax - R}{Rmax}$

$Rmax = \dfrac{1}{\gamma} \operatorname{Log} (I_o / In)$

$R = \dfrac{1}{\gamma} \operatorname{Log} (I_o / 2)$

I_o = MM Intensity at the epicenter

γ = Attenuation coefficient of Intensity with distance.

Rmax Is physically the distance between the epicenter and - the point where the maximum intensity has been measured and defines the radius of area of maximum intensity.

R Is the distance between the epicenter and the isosistal line 2 in the MM scale, where this intensity has been - defined as the minimum intensity of perpceptibility.

The ISR defined in this fashion is always less than 12 and greather than zero.

Using the known relationship between intensity (In) and ground acceleration, the ISR map can be transformed in maximum ground acceleration map, very useful for civil engineering design.

The procedure in constructing the ISR map is as follows:

1. From the local Seismicity (historical and present records) the normalized (depth) local magnitude has been calculated for each seismic event and plotted into a map by its coordinates.

2. From the known local relationship between maximum intensity and local magnitude established from the events in which both parameters have been measured, the seismicity map may be transformed into an Intensity map.

3. Using the local Intensity attenuation factor based upon - isoseismals of known events, the area of perceptibility - may be found by calculating Io, Rmax and R.

4. By analyzing the local population and geology (estratigraphy, structural geology) a density factor and geology factor may be assigned to each plotted intensity point.

5. With all those parameters the ISR may be constructed.

The results of such analysis for the Bolivian Seismic Risk problem are the following:

LOCAL MAGNITUDE

$$M_L = \log \left(\frac{A}{T}\right) + 1.8 \log (D) + 3.5$$

A = ground amplitude in microns
D = epicentral distance in degrees
T = period in seconds.

SEISMICITY

The seismic information includes sixty four years of analysis (1909-1972) used in the present work.

MAGNITUDE-MAXIMUM INTENSITY RELATIONSHIP

$$M_L = 2.05 + 0.4549 I_o$$

INTENSITY ATTENUATION WITH DISTANCE

$$In = 8.63\ 10^{-0.002109D}$$

D = Epicentral distance in degrees.

GEOLOGY

The following coefficients have been used

Granites and intrusive rocks	0.1
Cuarcites	0.3
Dolomites, Vulcanites	0.4
Sandstones	0.5
Shales	0.6
Conglomerates	0.8
Alluvials	1.0

POPULATION DENSITY

Which is a function of number of houses, factories, civil constructions etc. The density coefficients used are between 0.01 corresponding to 10^{-12} inhabitants/m2. and 1.0 corresponding - to 10^{6} inhabitans/m2.

ISR - MAP (Fig. 14)

With all the parameters calculated the ISR map was instructed for Bolivian territory, showing a maximum Index Seismic Risk - the region of Cochabamba, then follows Santa Cruz, Sucre-Potosí and Tarija, and finally La Paz-Oruro.

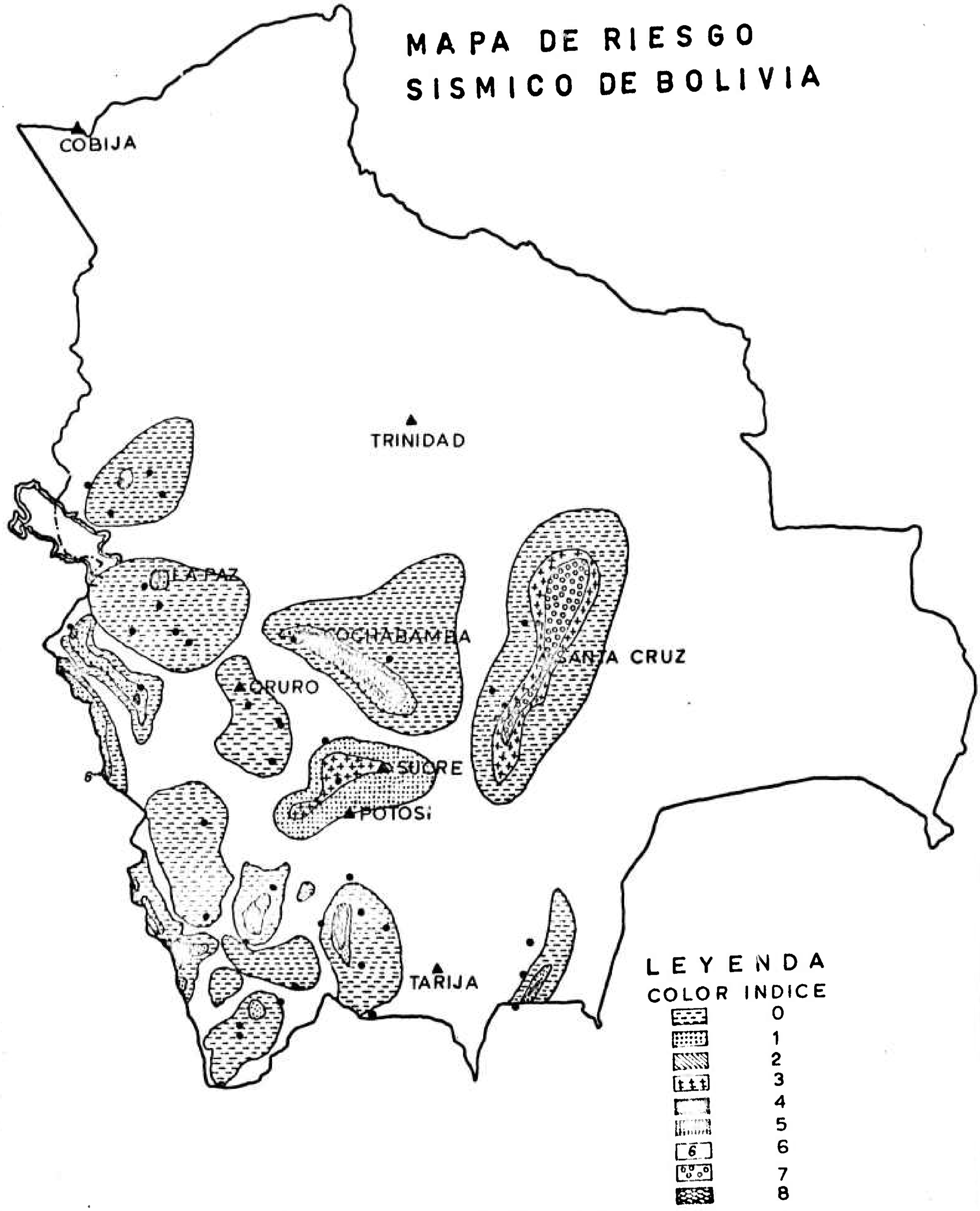


Fig. 14.- Bolivia seismic risk map, as explained in the text. Main towns indicated for reference.

PUBLICATIONS
(Partially sponsored by Grant 72-2397)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A High-Gain Long-Period seismic station (ZLP) was installed in a tunnel 90m long in the Zongo Valley (16°16'10.3"S, 68°07'05.3"W, 4397m asl), where daily barographic changes do not exceed 3 mbars, to obtain high quality data both for Federal agencies research and for Observatorio San Calixto research. A microbarograph and standard meteorological instruments were added for convenient correlations. Also short-period seismographs, with a gain of one million

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19 (continued)

Discrimination
Love and Rayleigh waves
Nazca plate
South American plate
Seismicity
Seismic risk

20 (continued)

for one second of period, were installed.

Operation has been maintained and magnificent records were and are still being produced. Vertical seismic noise of 20 through 100 sec of period was proved to be produced mostly by atmospheric disturbances, with a numerical relation of 2.5 to 5 millimicrons/microbar; horizontal waves are associated with wind.

The coefficients of the formula for calculation of seismic events local magnitude were found to be as it follows: $M_L = \log (A/T) + 1.5 \log D + 2.0$, for distances around 5 degrees. M sub L

The study of internal structure of the earth has shown an important friction in the earthquakes occurring at the lithosphere bending. Models were developed and are presented for the seismic velocities as a function of depth beneath La Paz region, differing a little from one azimuth to another.

Several techniques were tested to discriminate explosions from natural earthquakes; both Love and Rayleigh waves are quite better developed for earthquakes than for explosions; the ratio $A_Q:T_Q/A_R:T_R$ is much greater for earthquakes than for explosions in most of the spectrum. Surface waves dispersion definitely is not useful for such discrimination.

Subducted Nazca plate appears in different strips undulated or broken apart, according to the angle offered by South American plate. Correlations were done between gravity, strain release and metallogenesis as related to the subducted Nazca plate: a close relation was found (but the study has to be continued).

As a contribution to seismicity studies, the main results of a particular earthquake are presented, together with a preliminary seismic risk map estimated according to epicenter locations and macroseismic data.

An attempt of Rodríguez and Vega to quantify seismic risk, by defining relative weight of maximum MM intensity at a given distance, population density, area geology and attenuation of intensity with distance, is presented together with a map applying theory to Bolivia; the highest risk appears in the Cochabamba Valley.